Coherent noise remover for Optical Projection Tomography

Liangliang Shi[a], Di Dong[a], Yujie Yang[a], Jun Wang[b], Alicia Arranz[c], Jorge Ripoll[d], Jie Tian[**a]

[a]Intelligent Medical Research Center, Institute of Automation, Chinese Academy of Sciences, P. O . Box 2728, Beijing, 100190, China;
[b]School of Automation, Harbin University of Science and Technology, Harbin 150080, China;
[c]Swiss Federal Institute of Technology (ETH-Zurich), Institute for Biomedical Engineering, Switzerland;
[d]Universidad Carlos III of Madrid, Department of Bioengineering and Aerospace Engineering, Madrid 28911, Spain

ABSTRACT

Optical Projection Tomography (OPT) is a 3-Dimentional (3D) imaging technique for small specimens between 1mm and 10mm in size. Due to its high resolution and whole-body imaging ability, OPT has been widely used for imaging of small specimens such as murine embryos, murine organs, zebra fish, and plant sections. During an OPT imaging experiment, the ring artifacts are very common which severely impact the image quality of OPT. A ring artifact is caused by a bad pixel on the camera, or impurities on surface of lens and index matching vessel. Here we term these noises as coherent noise because they stay in the same image region during an OPT experiment. Currently, there is still no effective method to remove coherent noises. To address this problem, we propose a novel method to suppress the coherent noises before 3D OPT reconstruction. Our method consists of two steps: 1) find bad pixel positions on a blank image without specimen by using threshold segmentation, then fix the bad pixels on the projection image by using average of their neighbor pixels, 2) remove remained coherent noises on the sinogram by using Variational Coherent noise Remover (VSNR) method. After the two steps, lots of method can be used to generate the tomographic slices from the modified sinograms. We apply our method to a mouse heart imaging with our home-made OPT system. The experimental results show that our method has a good suppression on coherent noise and greatly improves the image quality. The innovation of our method is that we remove coherent noise automatically from both projection image and sinogram and they complement each other.

Keywords: coherent noise remover; optical projection tomography (OPT); sinogram

1. INTRODUCTION

OPT is a powerful tool for 3D observation of small biomedical specimens [1]. Owing to its ability to obtain both morphological imaging and molecular imaging in a single system with high resolution and sensitivity, a lot of fundamental studies about biological processes benefit from this technique [2,3,4]. However, OPT images suffer from several artefacts which reduce their overall quality of the 3D reconstruction images. There are some works which have been done to to improve its resolution, reduce artifacts and noise, and even expand its application to live imaging [5, 6, 7,8,9]. In OPT system, the bad pixels on the camera or the impurities in the system are unavoidable which will cause coherent noises on OPT projection images acquired from the system. The coherent noises make ring artifacts in the reconstructed tomographic slice after 3D reconstruction. Therefore, it is necessary to remove the coherent noises in OPT imaging. Conventional methods are semi-automatic methods which reconstruct 3D volume first, then mark the coherent noises by finding all ring artifacts manually, finally perform interpolation to compensate the noise pixels and reconstruct 3D volume again. These methods are inconvenient and lack robustness. To address this issue, we develop an approach to remove the coherent noises automatically with no prior 3D reconstruction. Instead of reducing the coherent noise through the projection images or the reconstructed 3D images, we will remove the coherent noise through each slice's sinogram

*Corresponding author: Jie Tian; Telephone: 8610-82628760; Fax: 8610-62527995; Email: tian@ieee.org; jie.tian@ia.ac.cn; Website: http://www.mitk.net; http://www.3dmed.net.

Medical Imaging 2015: Biomedical Applications in Molecular, Structural, and Functional Imaging, edited by Barjor Gimi, Robert C. Molthen, Proc. of SPIE Vol. 9417, 941723
© 2015 SPIE · CCC code: 1605-7422/15/$18 · doi: 10.1117/12.2081584

image, which is extracted from the projection images, by using Variational Coherent Noise Remover (VSNR) method [10,11,12].

The VSNR method proposed a stationary noise assumption (noise with a elemental pattern) replacing the white noise assumption. This suggests that we have no a prior knowledge on the location of the region of noise, but have a prior knowledge of the elemental feature of the noise. This assumption is very reasonable for the specific system. Specifically considering the OPT imaging, the coherent noise in the projection images will make the sinogram images of every slice emerge stripe noise. The noise model for images is not simply as $u_0 = u + n$, which u_0, u, n stand for the noised image, the image and the noise. The noise n would be replaced by convolving white noise with a pattern, which the white noise represents the location of the noise and the pattern represents the structure of the noise. Then the noise reduction problem is converted into estimate the noise's distribution. This can be solved based on maximum a posteriori probability.

The rest of the paper is organized as following: Section 2 introduces the coherent noise in OPT imaging and its influence on the quality of the reconstruction images, then the VSNR method is been expressed to reduce the noise in the sinogram images. In Section 3, the proposed method is applied to a mouse heart imaging with our home-made OPT system and the results are displayed and analyzed. Finally, the paper is concluded in Section 4.

2. METHOD

2.1 Coherent noises in OPT imaging

There are three main steps in OPT imaging. Firstly, multiple projection images with different angles around the sample are captured by the camera. Due to the imaging system, such as the bad pixels in the camera or the impurities on the lens, the projection images inevitably contains some noise. Secondly, for each slice to be reconstructed, its corresponding sinogram, which is shown in Figure 1(b), is extracted from the projection images. A sinogram is the angular sequence of the projection of a slice. Finally, the filtered-back-projection (FBP) method or other methods are used to reconstruct the slice from its sinogram. The 3D volume is the stack of all reconstructed slices.

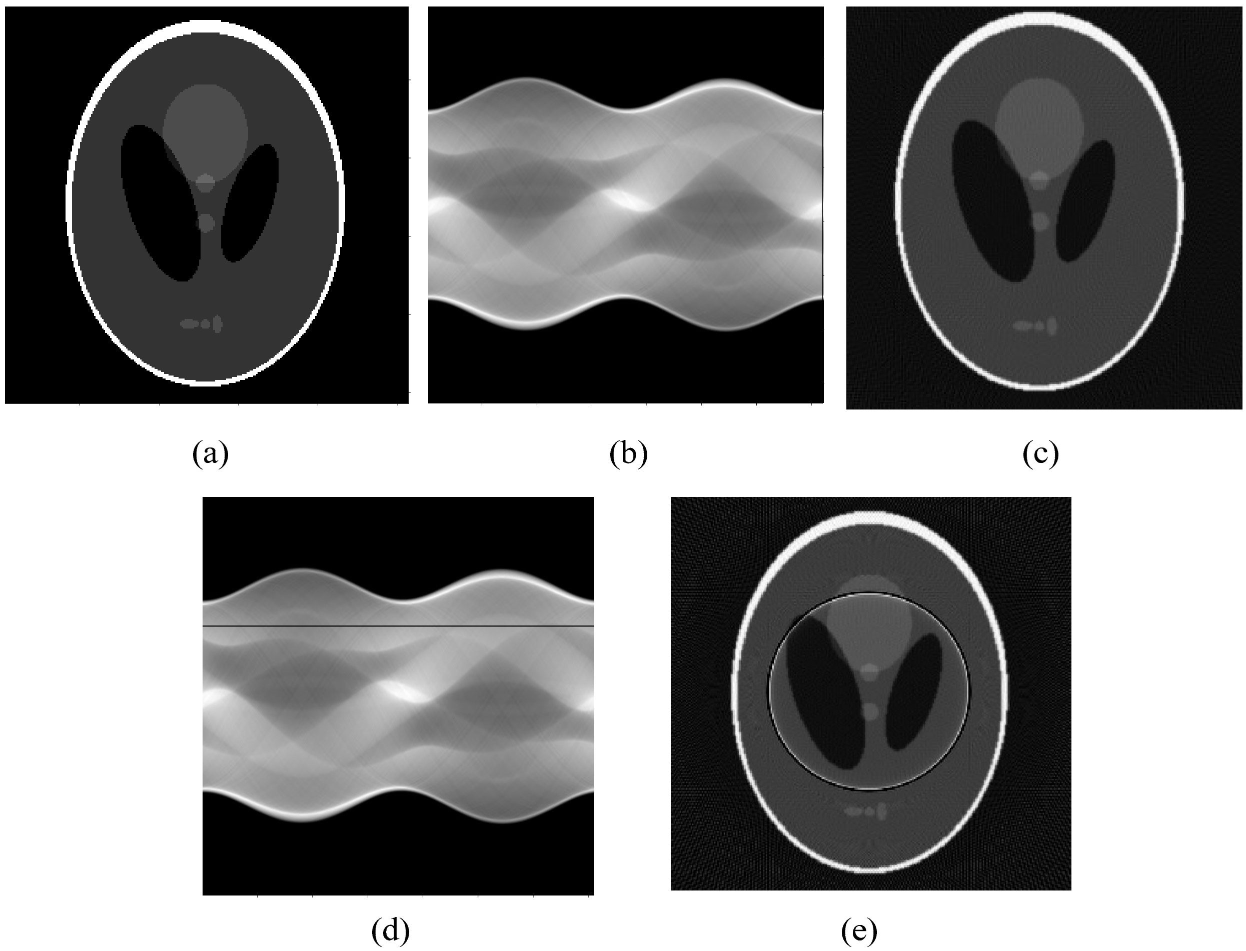

Figure 1 Impacts of coherent noise on reconstructed slice. (a) original phantom, (b) sinogram of (a), (c) reconstructed image of (b), (d) sinogram with coherent noise, (e) reconstructed image of (d).

In OPT, the light transmitted in small specimen can be expressed as a 2-D Radon transform:

$$g(\theta,l)=\iint_C f(x,y)\delta(x\cos\theta+y\sin\theta-l)dxdy\ , \tag{1}$$

where $f(x,y)$ is a slice to be reconstructed, which represents the light absorption factor map inside the specimens, $g(\theta,l)$ is the line integral of $f(x,y)$ along a certain line at a distance l from the origin and at an angle l with the axis in the system. If there are bad pixels in the camera or small impurities in the detection path, there will be dark pixels on each projection image at the same position. Consequently, the bad pixels would exist in the corresponding sinogram images at some angular, which is exactly some bad lines in sinogram images. As shown in Figure 1 (d), the coherent noise causes a stripe in sinogram compared with normal sinogram in figure 1 (b). Figure 1 (c) and (e) are the FBP reconstruction results from Figure 1 (b) and (d), which show that the coherent noise cause a severe ring artifact and lead to poor image quality, because it obscures the actual samples and hinders resolving of fine details, especially those region near the rotation axis [13]. In Optical Diffraction Tomography (ODT), there is a similar problem of ring noise. Kostencka J et al. [13] proposed a method which moves the position of a sample from the typical location on the rotation axis to an off-axis position. But this method maybe make the sample run out of the Field of View (FOV) when the sample is rotating, especially for some OPT system's FOV is not very big.

2.2 Coherent noise remover

The workflow of this method is displayed in Figure3. After collecting the raw projection images, we first remove the obvious noise dot on the projection images by threshold segmentation; secondly, the processed projection images would be extracted to combine the sinogram images as conventionally; thirdly, the sinogram images would be reduce the coherent noise by VSNR method; finally, the FBP method would be used to reconstruct the slice images.

Figure 2 Workflow of the coherent noise reduction of OPT reconstruction.

Our coherent noise remover method includes two main steps: 1) fix the bad pixels on the camera and obvious impurities by using threshold segmentation and pixel interpolation, 2) remove the rest of coherent noises from sinograms by using VSNR method.

In the first step, we fix bad pixels directly from the projection images. If there are bad pixels on the camera and obvious impurities attached in the lens, they would cause dark dots in the projection images. Therefore, we acquire a bright image with the light on but no specimen prior to the OPT experiment. The dark dots caused by bad pixels and impurities have low image values. We segment the abnormal regions by using threshold segmentation from the bright image. Then we mark the positions of the abnormal regions and start OPT experiment with the specimen. Once we acquire a projection image, the abnormal pixels are replaced by the average of their neighbor 8 pixels. After this step, most of the bad pixels are restored. But there are still some coherent noise point remaining in the projection image.

In the second step, we remove the rest of the coherent noised from the sinogram images by using VSNR method. After the OPT data acquisition, we extract all sinogram images from the projection images. The remaining noises produce stripes in the sinograms. The VSNR is a powerful denoising method for stationary noises [3]. The stripe noise is one of the stationary noises. Thus, we utilize VSNR to remove stripe noises from the sinograms. As shown in Figure 1(d), a sinogram with stripe noise can be modeled as

$$u_0 = u + \sum_{i=1}^{m} \lambda_i * \psi_i \ , \tag{2}$$

Where, u_0 is the sinogram with stripes, u represents the sinogram without noise. λ_i is independent realizations of white noise process with known probability density functions $P(\lambda_i)$ and ψ_i is the noise elementary pattern. In this application, the denoising process is assumed as Bernoulli process, and the noise pattern is assumed as stripe. Above all, we can get:

$$P(\lambda_i) \propto \exp(-\alpha_i \left\|\lambda_i\right\|_1) \, , \tag{3}$$

$$\psi(x, y) = \exp(-\frac{x^2}{\sigma_x^2}) \, , \tag{4}$$

Above all, the denoising process can be viewed as the following optimization problem:

$$\arg\min\left(\left\|\nabla(u_0 - \sum_{i=1}^{m} \lambda_i * \psi_i)\right\|_1 + \sum_{i=1}^{m} \varphi_i(\lambda_i)\right). \quad (5)$$

Therefore, we use VSNR to solve this optimization problem and remove the stripes in all sinograms. Finally, we utilize the conventional FBP method to reconstruct the 3D volume.

3. RESULTS

The proposed method was tested on a mouse heart imaging experiment by our prototype Optical Projection Tomography system. To validate the performance of our method, we compared our results with the direct FBP reconstruction method. The comparative results are shown in Figure 3, where (a)-(d) show the reconstruction slices and magnification images without denoising, and (e)-(h) present the reconstruction slices and zoomed images with our method.

Comparing with the Figure 3(f), the ring noise in Figure 3(b) makes the structure of the mouse heart blurred. Especially, at the region near the rotation axis the noise distort the image seriously. In Figure 3(f), after removing the coherent noise, the ring artefacts disappear and the structure of the mouse heart is clear. Comparing with the Figure 3(g), the Figure 3(c) has a bad dark ring covers the structure of the mouse heart. The bad dark ring was generated by the bad pixels dot in the projection images. In Figure 3(g), after removing the bad pixels dot by threshold segmentation, the bad dark ring is completely removed. What's more, we can see the Figure 3(h), which is the zoomed image of Figure 3(g), the ring noise is reduced by the sinogram using VSNR method. Above all, the results demonstrate that our method can effectively remove the coherent noise and improve the image quality.

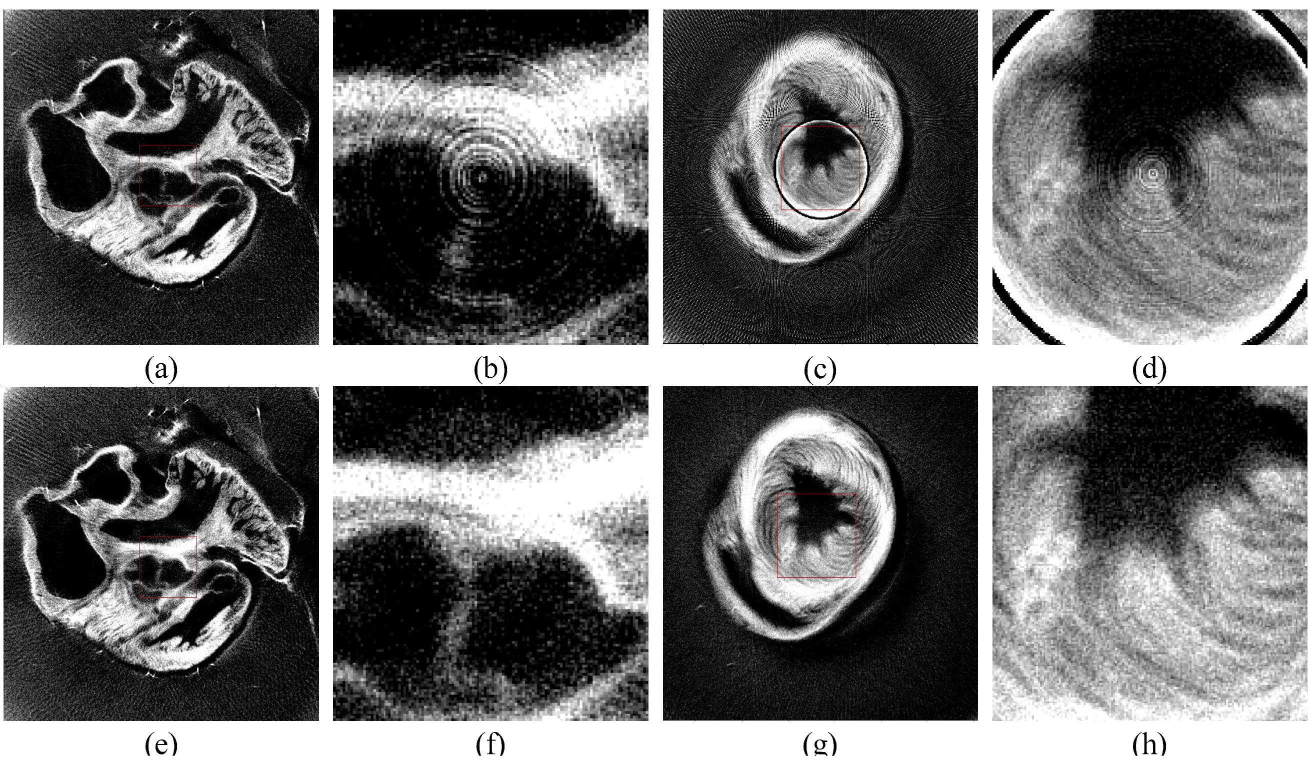

Figure 3 Comparative results of conventional FBP and our method on a mouse heart OPT experiment. (a) a reconstructed slice with conventional FBP method, (b) zoomed image of (a), (c) another reconstructed slice with conventional FBP method, (d) zoomed image of (d), (e) a reconstructed slice with our method, (f) zoomed image of (e), (g) another reconstructed slice with our method, (d) zoomed image of (h).

4. CONCLUSIONS

In this paper, we have proposed a novel approach for the coherent noise correction, which is suitable for bad camera pixels and impurities in OPT system. In our method, severe coherent noises are removed directly from the projection images by using a bad pixel map. Furthermore, the rest of the coherent noises are corrected by using VSNR method. The experimental results demonstrate that the proposed method can dramatically improve OPT's image quality through suppressing coherent noises.

ACKNOWLEDGMENT

This work is not being and has not been submitted for any publication or presentation elsewhere. This work was supported in part by the National Basic Research Program of China (973 Program) under Grant No. 2011CB707700, the National Natural Science Foundation of China under Grant No. 81227901, 81027002, 61231004, 81101095, and the Instrument Developing Project of the Chinese Academy of Sciences under Grant No. YZ201164. A. Arranz acknowledges support from the Marie Curie Intra-European Fellowship program IEF-2010-275137. J.R. acknowledges support from EC FP7 IMI project PREDICT-TB, the EC FP7 CIG grant HIGH-THROUGHPUT TOMO.

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